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SENSITIVITY OF TRANSIT SEARCHES TO HABITABLE-ZONE PLANETS

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ABSTRACT

Photon-limited transit surveys in the V band are in principle about 20 times more sensitive to planets of fixed size in the habitable zone around M stars than G stars. In the I band the ratio is about 400. The advantages of a closer habitable zone and smaller stars (together with the numerical superiority of M stars) more than compensate for the reduced signal because of the lower luminosity of the later-type stars. That is, M stars can yield reliable transit detections at much fainter apparent magnitudes than G stars. However, to achieve this greater sensitivity, the later-type stars must be monitored to these correspondingly fainter magnitudes, which can engender several practical problems. We show that with modest modifications, the *Kepler* mission could extend its effective sensitivity from its current $M_V = 6$ to 9. This would not capture the whole M dwarf peak but would roughly triple its sensitivity to Earth-like planets in the habitable zone. To take advantage of the huge bump in the sensitivity function at $M_V = 12$ would require major changes in *Kepler*. However, the reduced photometric-precision requirements at $M_V = 12$ makes a search for these transits possible from the ground. Photometric stability requirements are much less severe for M stars than G stars. To detect Earth-mass planets in the habitable zone around G stars, the variability on transit timescales must be less than 2×10^{-5}, but for middle M stars the limit is 1.2×10^{-3}.

Subject headings: occultations — planetary systems — techniques: photometric

1. INTRODUCTION

The first confirmed transiting planet, HD 209458b (Charbonneau et al. 2000; Henry et al. 2000), lies only 10 $R_\odot$ from its host G star, and therefore well inside the so-called habitable zone, where water could exist in its liquid state. All ongoing transit surveys are primarily sensitive to such "hot Jupiters" because their large diameters give rise to relatively strong (~1%) signals, while their proximity to their host increases the probability of transits occurring (Gilliland et al. 2000; Howell et al. 2000; Brown & Charbonneau 1999; Borucki et al. 2001; Mallen-Ornelas 2003; Udalski et al. 2002; Burke et al. 2003; Street et al. 2000, 2003). Konacki et al. (2003) have confirmed transit candidate OGLE-TR-56, which proves to have an even tighter orbit than HD 209458b.

While gas giants are not expected to themselves be habitable regardless of their location, they could have water-laden moons like Europa, Ganymede, and Callisto, which could support life if the planet lay in the habitable zone. Future ground-based surveys could be sensitive to such habitable-zone giant planets. Moreover, the planned *Kepler*[1] and *Eddington*[2] missions have as either their primary or secondary goals the detection of planets down to Earth size in or near the habitable zone. The *Kepler* and *Eddington* targets would be even more direct analogs of the Earth.

Here we investigate the sensitivity of transit surveys to planets in the habitable zone as a function of stellar type. We derive two remarkable conclusions. First, transit surveys are most sensitive to habitable-zone planets orbiting middle M stars ($M_V \sim 12$), despite the fact that they are most sensitive overall to planets orbiting early G stars ($M_V \sim 4$). Second, to achieve this sensitivity to dim stars, the survey's magnitude limit must be an extremely strong function of spectral type. Specifically, it must be about 7 mag fainter for middle M stars than G stars. Since such variable requirements can significantly affect survey design, they deserve careful analysis and consideration. For example, we show that unless the *Kepler* mission extends its magnitude limit for M stars well beyond its current (type independent) limit of $V = 14$, it will lose most of its potential sensitivity to habitable-zone planets. More strikingly, we show that it is easier to detect habitable-zone planets around $M_V = 12$ stars from the ground than from space.

2. SENSITIVITY TO HABITABLE-ZONE PLANETS

Pepper, Gould, & DePoy (2002) showed that if every star of luminosity L and radius R has a planet of radius r in a circular orbit of semimajor axis a, then a photon-noise-limited transit survey will detect

$$N(L,R,r,a) = \frac{\Omega d_0^3}{3} n(L,R)\eta \frac{R_0}{a_0}\left(\frac{L}{L_0}\right)^{3/2} \times \left(\frac{R}{R_0}\right)^{-7/2}\left(\frac{a}{a_0}\right)^{-5/2}\left(\frac{r}{r_0}\right)^{6} \quad (1)$$

planets. Here $n(L,R)$ is the number density of stars of the specified type, Ω is the angular area of the survey, and d_0 is the distance out to which an equatorial transit can just be reliably detected for the fiducial parameters L_0, R_0, r_0, and a_0. This equation assumes that stars in the field will be monitored out to the distance $d(L,R,a,r)$ at which an equatorial transit can be detected and so to the *corresponding apparent magnitude limit* determined by this distance and the absolute magnitude of the stellar type. It also assumes (as shown by

[1] Additional information is available at http://www.kepler.arc.nasa.gov/.
[2] Additional information is available at http://sci.esa.int/home/eddington/index.cfm.

Pepper et al. 2002) that detectability of transits depends essentially only on the total *eclipse-signature signal-to-noise ratio* (S/N) of all transits combined, rather than the characteristics and distribution of individual transits considered separately. The numerical factor $\eta \simeq 0.719$ arises because the volume probed by the survey is smaller by a factor $y^{3/2}$ for nonequatorial transits, where y is the ratio of the transit chord to the stellar diameter.

The equilibrium temperature of a planet (and thus whether water can exist in liquid phase on the planet surface) is the same if $a \propto L_{\rm bol}^{1/2}$, where the bolometric luminosity $L_{\rm bol}$ is to be distinguished from L, the luminosity in the band of observation. Hence, the relative sensitivity of a transit survey to habitable-zone planets is

$$N \propto nL^{3/2}R^{-7/2}L_{\rm bol}^{-5/4} \ . \quad (2)$$

Here we assume that all planets have the same albedo and neglect atmospheric effects. If we compare, for example, G stars ($M_V = 5$) with middle M stars ($M_V = 12$), the ratios of the various factors are $N_{12}/N_5 \sim 6 \times 630^{-3/2} \times 4^{7/2} \times 80^{5/4} \sim 10$. Note that if we were comparing detectability at the *same semimajor axis* rather than the *same habitability*, the last factor would not have entered, and the ratio would have been 0.05. Hence, while the sensitivity to planets in general is completely dominated by G stars, the sensitivity to habitable-zone planets is completely dominated by M stars. That is, the lower luminosities (and so smaller semimajor axes) combined with the smaller radii and greater numerical density of M stars more than compensate for the reduced photon counts.

In Figure 1, we show the sensitivity to habitable-zone "Earths" and to Earths all at the same semimajor axis (taken to be 1 AU). That is, the histograms show the total number of planets N that will be detected as a function of M_V assuming that each star in the field has one Earth-sized planet in the habitable zone or, respectively, one such planet at 1 AU. (The two histograms cross near $M_V = 5$ because the habitable zone is then at 1 AU.) The absolute normalization of this plot is set according to the characteristics of the *Kepler* mission ($7.8 \times 10^8 e^-\ \mathrm{hr}^{-1}$ at $V = 12$, $\Omega = 105\ \mathrm{deg}^2$, $A_V = 0.3$, mission-total S/N = 8 required for detection), but the form of the histogram would be the same for any photon-limited survey. The normalization for any other planet size should be multiplied by a factor $(r/r_\oplus)^6$, and the normalization for any other fixed semimajor axis should be multiplied by $(a/\mathrm{AU})^{-5/2}$ (see eq. [1]). The figure is constructed assuming that detection is in the V band. The effect of substituting other bands is approximately to change the slope of the histogram. For example, since the slope of the main sequence is $dM_V/d(V-I) = 3.37$ (Reid 1991), substitution of the I band would lead to an increase of slope $d\Delta \log N/dM_V = (3/2) \times 0.4/3.37 = 0.178$. That is, middle M stars would gain relative to G stars by an additional factor $10^{7\times 0.178} = 18$.

To compute these histograms, we follow the procedure of Pepper et al. (2002). An important feature of the color-magnitude diagram is that while the main sequence is fairly narrow for $M_V > 6$, it broadens for brighter stars (because of faster stellar evolution), so that a star of a given M_V can have a large range of colors. Thus, for the well-defined lower main sequence, $M_V > 6$, we consider the luminosity function (Bessell & Stringfellow 1993; Zheng et al. 2001) in 1 mag bins and evaluate the stellar radius at the center of each bin using the linear color-magnitude relation of Reid (1991), the color/surface-brightness relation of van Belle (1999), and the *VIK* color-color relations from Bessell & Brett (1988).

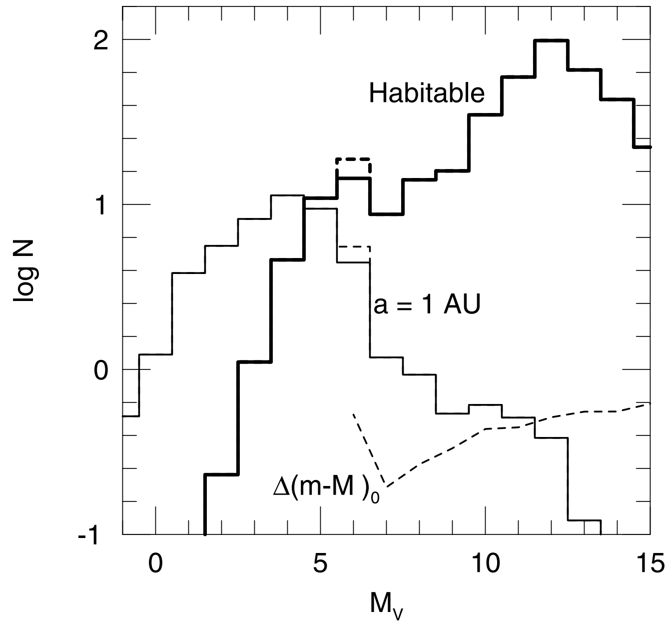

Fig. 1.—Total number of planets detected in the habitable zone (*bold histogram*) and in 1 AU orbits (*solid histogram*) as functions of absolute magnitude M_V (assuming every star has one such planet). The absolute normalizations have been set to Earth-sized planets and to the characteristics of the *Kepler* mission, but the form is completely general assuming observations in the V band. In the I band, the slope would be tilted upward toward faint stars. Extinction has been taken into account, but stellar variability and binarity have not. The calculation uses different methods for early ($M_V \le 6$) and late ($M_V \ge 6$) stars. The solid and dashed histograms compare the two methods in the one bin of overlap. The dashed curve shows the difference (relative to Sun-type stars) in the limiting distance modulus to which stars of different M_V must be monitored to achieve the sensitivity shown by the "habitable zone" histogram. Since this curve is basically flat, dimmer stars must be observed to the same distance and hence to much fainter apparent magnitudes.

On the other hand, for the upper main sequence $M_V < 6$ we evaluate the histograms directly using the *Hipparcos* catalog (ESA 1997). For example, the luminosity function for $M_V = 4$ is computed by summing $\sum_i [(4/3)\pi D_i^3]^{-1}$ over all stars within the *Hipparcos* completeness limit, $V < 7.3$, having $3.5 < M_V < 4.5$, and lying within 50 pc. The distance D_i is the minimum of 50 pc and the distance at which the star would have $V = 7.3$. Then, the constant-semimajor-axis histogram is computed by summing (and appropriately normalizing) $\sum_i L_i^{3/2} R_i^{-7/2} [(4/3)\pi D_i^3]^{-1}$, while the habitable-zone histogram is found by summing $\sum_i L_i^{3/2} R_i^{-7/2}\ L_{\mathrm{bol},i}^{-5/4} [(4/3)\pi D_i^3]^{-1}$. The stellar radii are determined from *Hipparcos*/Tycho (B_T, V_T) photometry and the color/surface-brightness relation of Gould & Morgan (2003), ultimately derived from van Belle (1999). We evaluate $L_{\rm bol}$ using bolometric corrections as a function of $V - I$ color derived from Binney & Merrifield (1998) and Bessell & Brett (1988) at the bright end and Reid & Gilmore (1984) at the faint end.

3. MAGNITUDE LIMITS FOR HABITABLE-ZONE PLANETS

To achieve the sensitivities calculated in § 2, one must analyze the light curves of all the stars being probed. This statement would appear so obvious as not to be worth mentioning. However, as we now show, dim stars are being probed at substantially fainter apparent magnitudes than are their more luminous cousins. Hence, to avoid losing most of the sensitivity of a transit experiment one must set different magnitude limits (i.e., different limiting flux levels to which stars are monitored) for stars of different M_V.

Let $m_{\rm lim}$ be the apparent magnitude at which the survey achieves the minimum acceptable total S/N (integrated over all transits) for a planet of radius r and semimajor axis a circling an $M_V = 5$ star. Consider an identical planet circling an $M_V = 12$ star in the same orbit and at the same apparent magnitude. Since the star's radius is a factor 4 smaller, the S/N will be a factor $4^2 \times 4^{-1/2} = 4^{3/2}$ times larger. The first factor comes from the fact that the planet occults a larger fraction of the stellar surface; the second comes from the reduced total time spent in transit ("duty cycle") due to the smaller radius. Now, the bolometric luminosity of the dimmer star is down by a factor 80, so to keep in the habitable zone, the planet must be moved closer by a factor $80^{1/2}$. This increases the transit duty cycle by the same factor and so increases the S/N by $80^{1/4}$. Combining these two effects with the usual dependence of S/N on flux implies $\mathrm{S/N} \propto \mathrm{flux}^{1/2} L_{\rm bol}^{-1/4} R^{-3/2}$. Hence, to maintain the same S/N, one must increase the magnitude limit by

$$\Delta m_{\rm lim} = 0.5 \Delta M_{\rm bol} - 7.5 \Delta \log R \ . \quad (3)$$

For the example just given, $\Delta m_{\rm lim} = 6.9$, i.e., a factor 570 in flux. Note that $\Delta m_{\rm lim}$ does not depend on the passband of observation. The dashed curve in Figure 1 shows the difference in the maximum distance modulus relative to the Sun at which a habitable-zone planet (of given radius) can be detected. Specifically, $\Delta(m - M)_0 = (V_{\rm lim} - M_V) - (V_{{\rm lim},\odot} - M_{V,\odot})$. For V-band observations, this offset is roughly constant over 10 mag. That is, the limiting magnitude required to achieve the sensitivities shown by the bold histogram increases approximately in lock step with M_V. This behavior can have major consequences for the design of transit experiments.

4. APPLICATION TO *KEPLER*

Photon-limited observations are not routinely achievable over very large dynamic ranges. A number of effects can intervene at fainter magnitudes. First, once the stars fall below the sky, the number of detected systems no longer falls as $L^{3/2}$ (see eq. [1]) but as L^3. That is, once the sky is reached, detections would fall off by a factor $\sim$4 per magnitude relative to the bold histogram in Figure 1. Second, if the exposure times are set so as not to saturate the brightest target stars (say 2 mag brighter than the mag limit appropriate for $M_V = 5$), then the flux levels will be a factor $\sim$4000 times lower at the mag limit appropriate for $M_V = 12$. For many observing setups, this would render the flux levels comparable to the read noise. Third, a field that is very uncrowded at one magnitude may well be extremely crowded 7 mag fainter, and this may interfere with doing photon-limited photometry. Hence, it is unlikely that all of the potential shown in Figure 1 can be achieved in any given practical experiment. Nevertheless, this potential is so great that it is worth thinking about how to achieve as much as possible.

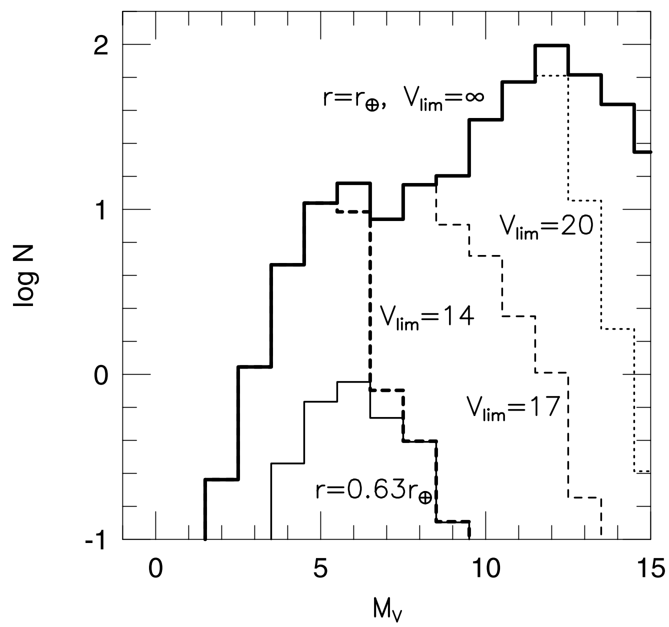

Fig. 2.—Total number of planets detected normalized to characteristics of *Kepler* and under various assumptions. *Bold solid histogram*: Each star has one Earth-sized planet in the habitable zone, and all stars are monitored regardless of magnitude (same as Fig. 1). *Bold dashed histogram*: Same planet distribution, but now only stars $V < 14$ are monitored. *Thin dashed histogram*: Same planet distribution; $V < 17$ stars are monitored. *Dotted histogram*: Same planet distribution; $V < 20$ stars are monitored. *Thin solid histogram*: Planets have radius $r = 0.63\ r_\oplus$, and only $V < 14$ stars are monitored.

We first illustrate the type of trade-offs involved by considering the *Kepler* mission. The *Kepler* design calls for recording only stars $V < 14$, presumably to minimize data transmission. The magnitude limit required to detect Earth-like planets around Sun-like stars at $\mathrm{S/N} = 8$ is $V_{{\rm lim},\odot} = 13.6$. Hence, from the dashed curve in Figure 1, the required magnitude limit at $M_V = 6$ is $V_{\rm lim} = V_{{\rm lim},\odot} - M_{V,\odot} + M_V + \Delta(m - M)_0 = 14.4$, i.e., already somewhat fainter than the $V = 14$ limit adopted by *Kepler*. The volume probed, and hence the detections, fall relative to the bold histogram by a factor $(10^{0.2})^3 \sim 4$ for each magnitude beyond $M_V = 6$ (see Fig. 2). Hence, assuming that every star has one planet in the habitable zone, only a total of 28 will be detected.

Keeping the photometry information for stars to $V = 17$, for example, should increase the number of habitable-zone detections by a factor 2.5, while keeping stars with $V < 20$ would increase this number by a factor 9 (see Fig. 2). Of course, there are many obstacles to keeping information on stars this faint.

For example, there would be an enormous number of giant stars contaminating such a deep sample. In fact, however, it is straightforward to distinguish the later-type dwarfs from the much more numerous giants of similar colors using a reduced proper motion (RPM) diagram (Gould & Morgan 2003). The total number of such stars ($M_V \leq 12$, $d \lesssim 500$ pc) is only $\sim 3 \times 10^4$, far fewer than the $\sim 10^5$ giants in the field that could be eliminated using the same RPM diagram.

A more difficult problem is crowding. The *Kepler* point-spread function (PSF) is deliberately defocused to $10''$, meaning that the crowding limit is about 10 arcmin^{-2}. At the adopted *Kepler* sight line, $(l, b) = (69\overset{\circ}{.}6, 5\overset{\circ}{.}7)$, this limit is reached at $R_{\rm USNO} \sim 18.2$ (as determined by a query of the USNO-A catalog). If *Kepler* were redirected to $(l, b) = (70°, 15°)$, the density of stars down to $R_{\rm USNO} = 18.2$ would be 3.5 arcmin^{-2}, approximately 3 times lower. Hence, recovery of faint stars would be much easier. Presumably, *Kepler* has chosen to look right in the Galactic plane because of the higher overall star density. However, since the stars useful for transits mostly lie within 500 pc, a field at $b = 15°$ would lie only 130 pc above the plane, where the density of such target stars is only slightly lower than at the plane. Hence, the crowding problem could be substantially ameliorated at small cost.

The last problem is sky. At high ecliptic latitude, the sky in space is $V \sim 23.3$ arcsec^{-2}, or $V \sim 17$ in a $10''$ PSF. Hence, *Kepler* completeness appears to be fundamentally limited to stars at $M_V < 9$. As shown in Figure 2, detections from stars at $M_V \geq 10$ would be highly suppressed. Only contracting the PSF (which has been deliberately defocused to improve the photometry) could overcome this difficulty. (At $V \sim 17$, crowding would not be a serious problem even for the current Galactic plane line of sight.)

Because any project trying to detect habitable-zone Earths will be starved for photons, they are all likely to use much broader bandpasses than the standard Johnson V filter assumed in our calculations. Hence, if one defines equivalent "V response" at solar-type stars, then such a broadened filter will have greater sensitivity to M stars than will standard Johnson V. However, this difference has no qualitative impact on the above conclusions. For example, the *Kepler* design calls for a bandpass that is flat over 400 nm $< \lambda <$ 850 nm, but this increases the number of stars probed for habitable-zone Earths by 17% for $V < 14$ and 31% for $V < 17$, relative to the results shown in Figure 2 for standard Johnson V.

Finally, we note that the results reported here are a strong function of planet size. As remarked in § 2, the absolute normalizations in Figure 1 scale as r^6. By an argument similar to the one given in § 3, $\Delta m_{\rm lim} = 10\Delta \log r$. For example, for $r = 0.63\, r_\oplus$, the normalizations in Figure 1 would be reduced by a factor 16, while the required $V_{\rm lim}$ at each M_V would be brighter by 2 mag. Hence, in *Kepler*'s current configuration, it would retain full sensitivity to $M_V \sim 8$ stars and so would be able to detect ~3 planets (see Fig. 2), while if its coverage were extended 3 mag to $V_{\rm lim} \sim 17$, it could detect ~8 planets.

5. APPLICATION TO GROUND-BASED SEARCHES

A striking feature of Figure 2 is the huge spike in sensitivity at $M_V = 12$, which can only be mined if the survey can reach a limiting magnitude of $V \sim 20$. While *Kepler* cannot reach this limit because of its large PSF (see § 4), a properly designed ground-based survey could.

The key point is that the fractional depth of Earth-sized transits scales as $\delta \propto R^{-2}$, while the number of such transits during an experiment of duration T scales as $N \propto TM^{1/2} a^{-3/2}$. Hence, to achieve an integrated S/N = 8 over $T = 4$ yr, requires a fractional precision of

$$\sigma = 2 \times 10^{-5} \left(\frac{M}{M_\odot}\right)^{1/4} \left(\frac{R}{R_\odot}\right)^{-2} \left(\frac{L_{\rm bol}}{L_{\rm bol,\odot}}\right)^{-3/8} . \quad (4)$$

While systematics probably prevent the $\sigma = 2 \times 10^{-5}$ required for detection of Earth transits of solar-type stars from being achieved from the ground, the $\sigma = 1.2 \times 10^{-3}$ required for $M_V = 12$ ($M/M_\odot = 0.29$, $R/R_\odot = 0.25$, $L_{\rm bol}/L_{\rm bol,\odot} = 0.012$) stars might be within reach.

For illustration, we present a straw-man design. Place five telescopes, each modeled after *Kepler*, on equatorial mounts about 30° from the equator and point them directly at one of the celestial poles. Use a flat "R/I" filter (650 nm $< \lambda <$ 850 nm), which for $M_V = 12$ captures ~66% of the photons detected by the broader *Kepler* band and about equal to the number assumed in Figures 1 and 2. The $V = 20$ target stars will be the 18th mag in this filter, still well below the sky. Assuming that each telescope operates an average of 5 hr per day, and assuming photon-limited statistics, the sensitivity will be that shown in Figure 2, i.e., about 120 systems probed at $M_V = 11$ and 12. Because the field lies 27° from the Galactic plane and the target stars have a distance modulus $\lesssim 8$, their mean density is a factor 2/3 of that near the plane (Zheng et al. 2001), thus reducing the number of probed systems to 80. Note that because of the large number (~80) of transits, it would make no difference if any individual transit were missed because of weather (Pepper et al. 2002). One might not want to carpet the entire 105 deg^2 field with the ~4 μm ($0\overset{''}{.}67$) pixels needed for good photometry in ~$1\overset{''}{.}5$ seeing. One could instead place 10^4 individual small (e.g., 64 × 64) detectors in the focal plane, one at the position of each M dwarf. Differential refraction over the night would move stars relative to one another by $10''$, which sets the minimum size of the individual detectors.

6. OTHER EFFECTS

In estimating the number of stars that can be probed for habitable-zone planets, we have so far ignored binarity and stellar variability. In principle, binarity could affect planet detectability in two distinct ways: first by directly preventing the existence of a stable planet in the habitable zone, and second by effectively injecting two stars into the sample in place of the single blended "star" from the combined light. These effects are each fairly small and approximately cancel each other.

Assuming that a planet cannot exist within a factor 4 of semimajor axis of a binary companion, the period distribution of Duquennoy & Mayor (1991) excludes planets for 11% of all G stars. Next, if what is taken as a "single star" in the analysis of § 2 is actually an equal-temperature binary with relative fluxes $(1, f)$ and lying well outside the habitable zone, then the fractional depth of the transits around the individual components relative to the combined light will be exactly as assumed. The stellar radii will be smaller than assumed by factors $(1+f)^{-1/2}$ and $[f/(1+f)]^{1/2}$, but the habitable zones will be closer by the same factors, so both the probabilities of transit and the fraction of the total time spent in transit will be exactly the same. Hence, two stars will be monitored for the price of one, effectively increasing the total number of systems probed. However, if the companion is substantially down the main sequence and so has lower temperature and surface brightness, its transits will be essentially undetectable in the glare of the primary. Already at $M_V = 8$ ($M = 0.66\, M_\odot$), the V-band surface brightness is a factor 7 lower than that for the Sun. Duquennoy & Mayor (1991) find 10% of G stars with higher mass ratio than this and with periods $P > 10^4$ days. Hence, the enhancement due this effect is somewhat less than 10% and roughly cancels the previous effect.

For M stars, Fischer & Marcy (1992) find a similar companion mass-ratio distribution as G stars at the high-mass end, so the enhancement effect is of a similar magnitude. They find substantially fewer companions near the habitable zone, partly because the binarity rate is overall lower for M stars, but mainly because binary fraction per log semimajor axis falls toward smaller a (as it does also for G stars). Hence, the correction for binaries is slightly more positive for M stars than G stars, but still small.

If stellar variability exceeds the level given by equation (4) ($\sigma = [2, 35, 120] \times 10^{-5}$ for $M_V = [5, 10, 12]$) on timescales of a transit (13, 3, and 2 hr), then the planet cannot be reliably detected. That is, the light curve must be well fitted by a (2-parameter) straight line over roughly 10 times this duration, so that longer term variability can be effectively removed. The Sun satisfies this constraint, and based on Ca II H and K emission, Henry et al. (1996) conclude that the general G star population is bimodal, with 30% substantially more active than the Sun. While M star variability has been studied on long timescales (Stokes 1972; Weis 1994) there are no such studies on the relevant few-hour timescales and at the required millimagnitude levels. Hence, this remains the biggest uncertainty regarding the viability of M star transit searches.

The fraction of M stars with gas-giant companions is substantially lower than that of F/G/K stars. There are no rigorous published studies, but D. Fischer (2003, private communication) notes that while 70 of 1200 F/G/K stars in their program have detected planets, this is true for only one out of 120 M stars. By Newton's Third Law, M star companions should be easier to detect than G star companions of similar mass. However, this says nothing about the relative frequency of terrestrial planets about which, at present, there is no information.

Finally, we note that there is some question about whether planets in the "habitable zone" around M stars can in fact be inhabited because their hosts show long-term variability (Turnbull & Tarter 2003) and because they are tidally locked (Joshi, Haberle, & Reynolds 1997). The latter authors study both effects and conclude that they can be, but this remains a subject of ongoing controversy.

In brief, the biggest uncertainty about the viability of a search for habitable-zone planets around M stars is their variability at few-hour timescales and millimagnitude levels. Some information relevant to this question may be derived from ongoing transit surveys because they have the required high cadence and have almost the requisite photometric precision. However, because the number of M dwarfs in magnitude-limited samples is extremely small, it is likely that a full answer will require a dedicated study of its own.

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